Flex Serv Manuf J (2012) 24:171–209
DOI 10.1007/s10696-011-9126-z

A two-stage sequential planning scheme for integrated operations planning and scheduling system using MILP: the case of an engine assembler

Jose P. Garcia-Sabater · Julien Maheut ·
Julio J. Garcia-Sabater

Abstract This paper presents an operations planning scheme based on mathematical programming models (specifically, Mixed-Integer Linear Programming (MILP) models) integrated into a web-enabled Advanced Planning and Scheduling System (APS), developed for and implemented in an engine assembler that supplies the car industry. One objective of this paper is to provide empirical insights into some operations planning characteristics in the automotive industry. The other main objective is to show MILP models and their use to create plans that enable the coordination of different planning levels (mid-term and short-term) and planning domains (procurement, production and distribution). The APS fulfills the requirements of an engine assembler in the automotive sector (namely lean-type constraints and objectives). The system is based on two MILP models, which have been purposely developed together along with their relations. The models presented herein provide a solution that considers supply chain objectives and constraints, and are integrated by means of data and constraints which have proven sufficient to fulfill users' and stakeholders' requirements. This case study presents the models' most relevant aspects and their implementation.

J. P. Garcia-Sabater (✉) · J. Maheut · J. J. Garcia-Sabater
ROGLE Departamento de Organización de Empresas, Universitat Politècnica de València,
Camino de Vera, s/n., 46022 Valencia, Spain
e-mail: jpgarcia@omp.upv.es; jpgarcia@upv.es

J. Maheut
e-mail: juma2@upv.es

J. J. Garcia-Sabater
e-mail: jugarsa@upv.es

J. P. Garcia-Sabater
Camino de Vera S/N, 46021 Valencia, Spain

Keywords Advanced planning and scheduling system (APS) · Mixed-integer linear programming (MILP) · Supply chain management (SCM) · Automotive industry · Just in time (JIT)

1 Introduction

Supply Chain Management (SCM) may be defined as: “the task of integrating organizational units through the supply chain (SC) and of coordinating the flow of material, information and financing for the purpose of fulfilling the client’s demands”(Stadtler and Kilger 2002). Dudek (2004) states three SCM objectives: improve service for clients; lower the amount of resources to serve clients; improve the SC’s competitiveness. Improving competitiveness lies on two main pillars: integrating the SC and coordinating it (Stadtler 2005). Coordinating the SC is, in turn, based on: using information and technology to improve the flow of information and materials; process orientation in order to accelerate the execution of processes and associated activities; and Advanced Planning (Stadtler 2005). Advanced Planning of the SC addresses decisions regarding SC design, its mid-term coordination and the short-term planning of processes. Advanced Planning systems attempt to fulfill the aforementioned objectives by using specific software (Fleischmann and Meyr 2003).

Many managers tend to think that Enterprise Requirements Planning (ERP) systems will solve their planning issues. Yet despite its name, ERP systems are usually transaction-based systems rather than planning systems (Chen 2001). Traditional production planning methods, such as Material Requirements Planning (MRP), consider only the availability of materials, and totally ignore factors such as capacity limits and SC configurations (Caridi and Sianesi 1999). Furthermore, planning functions in large companies are usually executed by different organizational units at different locations. The lack of coordination between these planning functions often results in excess inventories, poor customer service, and insufficient capacity utilization (Kannegiesser and Gunther 2011).

The broad extension of ERP systems has brought about the emergence of the so-called Advanced Planning and Scheduling Systems (Chern and Hsieh 2007) which may be viewed as “add-ons” of the ERP system to plan and optimize the SC (Rashid et al. 2002). An Advanced Planning and Scheduling System (APS) extracts data from the ERP systems, and supports decision making to reduce costs and inventory and increase manufacturing throughput and improve productivity (Lee 2002). Once the decision has been made, it is sent back to the ERP system for its final execution (Fleischmann and Meyr 2003). For this support, APS uses optimization techniques to model and determine the quantities to be produced, stored, transported, and procured by respecting real constraints of the SC (Günther and Meyr 2009). APS might help with the management of the whole SC, specifically its operations (Parush et al. 2007). There are many commercially available APS software (David et al. 2006). The various software modules cover all the segments of the operations planning throughout the SC, in all the planning horizons (Stadtler 2005). Although an interesting application may be found in

Sillekens et al. (2010), the use of Advanced Planning tools in the automotive industry is minimal (Meyr 2004). Perhaps this is because over the years, it has been claimed that the application of lean principles and the use of Information Technology are incompatible (Riezebos et al. 2009). It is not in vain that what is considered the first article in English on the Toyota Production System (Sugimori et al. 1977) suggests that the use of computer systems to organize logistics would introduce uncertainty and unnecessary costs.

Many Lean companies now use ERP/MRP methods to communicate demand through SC, and hybrid situations have become common in the automotive industry (Riezebos et al. 2009). Indeed, the need to coordinate capacitated transport and production together with low stock levels, and its relation with lean systems, is probably no small concern. MRP does not offer planning tasks in this sense (Drexl et al. 1994); instead, it supports planning, but only to a limited extent (Chung and Snyder 2000), and a program that works on the shop floor cannot be obtained through its use (Ho and Chang 2001). In fact, MRP systems are supplemented with spreadsheets into which data are manually gathered to develop production plans (Hahn et al. 2000). This lack of use of more Advanced Systems might be related with the complexity of the SC in the automotive sector (Choi and Hong 2002).

The research presented in this paper came about with the request of an IT Consultancy firm which had been asked to automate the operations planning process, which then involved several technical operators. The automotive company, with engine plants worldwide, had a proprietary ERP system that did not consider an Advanced Planning and Optimization module. The request characteristics included the development of a tool which exports results to an Excel spreadsheet so they can be modified. This paper shows the planning scheme based on mathematical programming that was developed in line with this request.

One of the main objectives of the paper is to provide new insights into the Operations Planning process, thus the paper is presented as a case study. The second objective is to propose a mathematical modeling approach to solve the problem by “satisficing” users’ requirements. Of course, the models proposed are not the only possible ones, but have been able to solve the issues which arose during the process.

This paper presents a successful implementation of a web-enabled APS that coordinates the SC of an engine assembler. Our case study includes an overview of mid-term master planning and short-term operations planning using MILP models, and demonstrates how coordination between business functions and temporal scales has been achieved. The framework used in this paper is similar to that presented by Meyr et al. (2005), which covers the main areas of any APS.

The remainder of the paper is organized as follows: first, an overview of the problem is introduced. Then, the different modules that have had to be generated are thoroughly described. Sections 4 and 5 introduce the designed and implemented models. Section 6 offers an overview of the system in which the models have been included, together with an implementation analysis and a summary of the new system’s advantages. The paper ends with a conclusion and a further research section.

2 Problem overview

2.1 The product and clients

An internal combustion engine is an assembly product composed of a variety of components that are manufactured and assembled on an assembly line (Wang and Sarker 2005). Although there are many other parts that are also assembled in the final product, the most relevant components, known as the 5Cs, are cylinder blocks, cylinder heads, crankshafts, connecting rods and camshafts (Lloret et al. 2009). Each component type is produced on a different and highly automated specific line.

The main clients of an engine assembly line are car assembly lines. The cost of backlogging those clients is very high since a car cannot be assembled without an engine.

The other clients of an engine plant are mainly spare part distribution systems and customized car builders (among these, R&D departments). These clients have very low demand and their backlogging costs are not that high.

Each client requires different engines, and the volume of each one might vary considerably (both from client to client and among different periods). For instance, a research center might request a few units per week, whereas a car assembly plant might require dozens or hundreds of units per day.

Overall demand in a normal week might be higher than 5,000 units. Yet fluctuations caused by clients' calendars (e.g., summer holidays) and the final demand of cars exist. Variety of final products (engines) has increased in the last decades. Some 25 years ago, the plant did not produce more than 4 or 5 types simultaneously, but nowadays, it can produce about 40 variants in the same week.

Moreover, engine components can also be sold elsewhere. The main external clients for components are the spare part operations system and other engine plants all over the world. Fluctuations in external demand for components are even greater than at the engine level.

The demand forecast is the result of a previous MRP explosion done through corporate software. The larger the product sales volume, the better the forecast. Demand has a 6-month horizon. It is very accurate for the first 4–5 weeks in the horizon, even though the demand in the final periods is most unreliable. Figure 1 represents the different elements and flows in the SC of the engine assembler.

Transport to clients might be by truck, ship, train, or even plane. In any case, the whole capacity should be used since transportation costs amount to almost 60% of logistics costs. In our case study, long distance and large quantities transport justifies the Full Truck Load (FTL) strategy (Bilgen and Günther 2009).

2.2 The supply chain topology

To better understand the SC planning problem in the case presented in this paper, Table 1 describes the functional and structural attributes of the component production lines and the engine assembly line.

The engine assembly line is a mixed model assembly line (MMAL); however, a multi-model assembly line has emerged in the last 15 years ago. Some

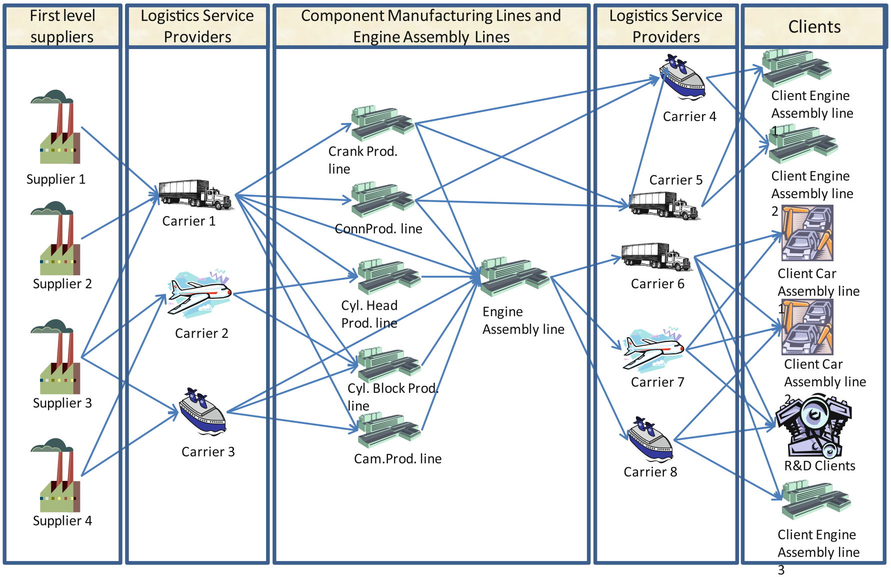

Fig. 1 Supply chain of an engine assembler scheme

characteristics of shorter complexity times have been kept, and they avoid the possibility of sequencing all the possible variants simultaneously. In fact, some of the line's physical characteristics are shown by limiting the constraints in the number of models to be assembled simultaneously. This line has no setup costs and does not require a setup time to change the model.

Component lines did not evolve from the multi-model assembly line concept, and their setup costs are highly relevant and sequence dependent. The setup process has evolved in order to avoid setup times.

The raw material for all five main components (the so-called 5Cs) is bought directly from different foundries with long lead-times. As previously mentioned, these engine factories frequently buy and sell components to other engine factories. There is limited capacity storage between both stages, and this storage capacity differs for the various lines since products are stored in different racks, and different tools are used to manipulate them.

The different supply modes presented in Boysen et al. (2009) also appear (to a lesser extent) on the engine assembly lines. The supply that a simple engine plant requires has to consider not only the foundries that deliver the five components which are the raw materials for the 5Cs lines, but also some plastic components and other subassemblies. Some suppliers are local, but with others, transit times can run to more than 10 weeks given the use of global suppliers for some components. These times can be unreliable owing to customs, shipping, and so on.

The operations planning process presented in this paper involves several departments. The main stream of the work was done together with the material planning and logistics department, but production, human resources, maintenance or

Table 1 Supply chain topology for the engine supply chain

Attributes	Component production lines contents	Engine assembly line contents
Functional attributes		
Number and type of products procured	Few, 3–7 major raw materials for each line	Important, 5 mains components (5Cs) and 350 commodities
Sourcing type	Single (Raw Material Family)	Single (for European Supplier) Multiple (for local Supplier)
Supplier lead-time and reliability	8–12 weeks for cylinder block and cylinder head and uncertain Short (days) and reliable for the others	Short (hours) for Products supplied in JIT and reliable Medium (days) and reliable for the others
Materials' life cycle	Long (1 year)	Medium (6 months) before small engineering changes
Organization of the production process	Flow line	Mixed model assembly line
Repetition of operations	Large batches (depends on the considered line)	Small batches
Changeover characteristics	Sequence dependence setup costs	
Bottlenecks in production	Known	Known
Working Time flexibility	Frequently used, additional shifts	Frequently used, additional shifts
Distribution structure	One stage	One stage
Pattern of delivery	Continuous FTL	Continuous FTL
Deployment of transportation means	Unlimited	Unlimited
Availability of future demands	Forecasted for external demand and orders for internal demand	Forecasted for external demand.
Demand curve	Stable, highly dependent on new product development	Stable, highly dependent on new product development
Products'life cycle	1 year	Several months
Number of product types	20	50
Degree of customization	Standard products	Standard products and some customized products
Bill of material (BOM)	I-Type	A-type and alternative BOMS
Portion of service operations	N.A.	N.A.
Structural attributes		
Network structure	Mixture	Mixture
Degree of globalization	International	International
Location of decoupling point(s)	Make to stock	Make to stock
Major constraints	Stock capacity Dependent setup Material availability	Manpower Capacity of assembly line Material availability

Table 1 continued

Attributes	Component production lines contents	Engine assembly line contents
Legal position	N.A.	N.A.
Balance of power	Customer	Customer
Direction of coordination	Mixture	Mixture
Type of information exchanged	Forecasts and orders	Forecasts and orders

quality department constrain the definition of the problem and/or use the results obtained.

3 The supply chain matrix in this case study

In this section, an overview of the planning needs in this case study is presented. The framework presented by Meyr et al. (2005), as seen in Fig. 2, was used to cover the main system areas. In this case study, mid-term corresponds to the 6-month planning horizon with bucket periods of weeks, while short-term planning corresponds to a 4-week planning horizon with daily buckets. Lastly, the daily scheduling tasks are solved with a 2-day horizon with variable buckets.

The structure of this section goes through the different planning levels, and covers domains such as the Supply Chain Planning matrix modules. The particular characteristics of the different APS modules implemented are highlighted.

The main characteristics of the models herein presented are similar, since both of them are operations planning models. The differences between them are those related with different horizons and periods. Therefore the main differences will show up in terms of objectives and constraints formulation than on their own definition.

3.1 Six-month master planning (6MMP)

Mid-term planning is usually divided into two main modules: Master Planning (MP) and Demand Planning. Demand Planning is not treated in this case study since it was defined by the other firm's levels. Our work proposes to solve the 6MMP, along with the 4-week operations planning, to synchronize the whole network flow of materials on a mid-term basis.

According to several authors, the planning horizon comprises at least one seasonal cycle, typically 1 year (Stadtler 2005). In our case the planning horizon should at least cover until the end of the next long holiday period (Easter, Summer, Christmas).

The 6-month plan presented in this case study not only considers the capacity planning activities at the production level, but also includes material requirements,

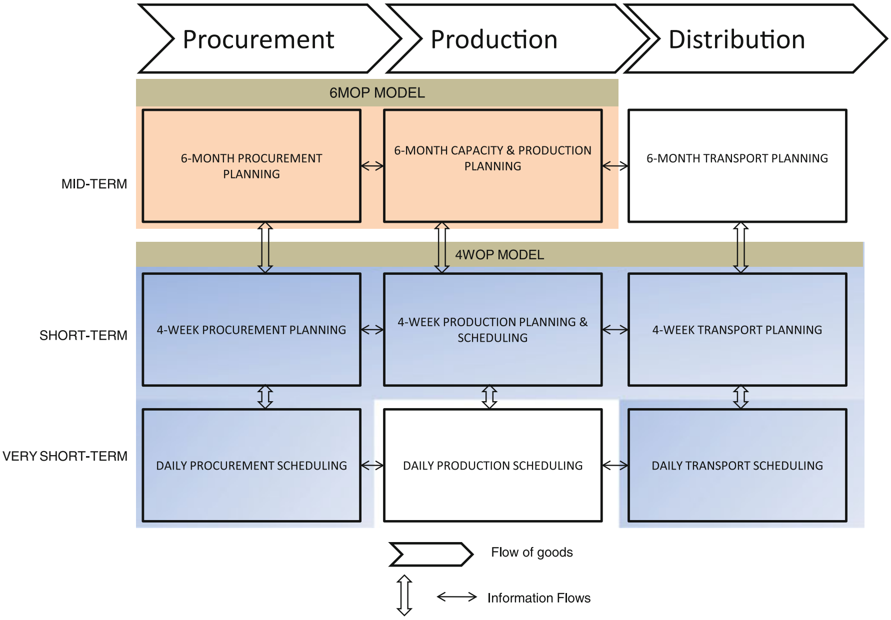

Fig. 2 Coverage of the mathematic models implemented in the APS in this case study

production and transport planning at a reasonable detailed level. With this horizon, transport planning activities are usually considered to select transport modes. However, these decisions are beyond the scope of the case study presented herein, which also happens with supplier selection activities.

To better understand the planning tasks, objectives, constraints and decisions to be taken at this level, a summary is proposed in Table 2. This table describes it by separating the functional areas of procurement, production and distribution that are considered in the same model.

The 6MMP process delivers plans for each functional area:

- 6-month capacity production plans for all five production lines and the assembly line, including production rates and the working calendars.
- 6-month production plans for each line for the purpose of setting stock levels at the end of each week with the 6-month horizon.
- 6-month material requirements plans for short-distance suppliers and a 6-month detailed material procurement plan for long-distance suppliers.

As explained later, the mathematical model is used in two separate instances: first, to help define the 6-month capacity production plan; second, the production levels have to be defined together with the rest of the plans.

In the 6-month master planning, 6-month transport planning has not been incorporated since it confers great complexity to the modeling problem and it is usually done at the 4-week level. So, after some meetings with the staff related to the problem, it was decided to not include it in the mathematical planning.

Table 2 6MMP characteristics

	Procurement	Production
Tasks	Raw material requirement planning for short-distance suppliers	6-month master production planning
	Ordering raw material for long-distance suppliers	
Objectives	Minimize raw material stock levels	Minimize total operating costs (minimization of productive days and extra days production)
		Minimize storage costs
		Maximize the stability of the plans
Constraints	Working calendars	Working calendars
	Lead-time of long-distance suppliers	Production rates
	Raw material in transit	Safety stocks levels
		Storage capacity limits
		Availability of raw materials and components
Decisions	6-month material requirements plan for short-distance suppliers	6-month capacity production plans (new working calendars; adjustments in production rates capacity)
	6-month detailed material procurement plan for long-distance suppliers	6-month production plans for each line

3.1.1 6-month capacity production plans

Wang and Liang (2004) state that MP aims at determining the best means of meeting demand by adjusting production capacity (workforce levels, overtime, outsourcing, contracting, etc.) and stock levels.

Piper and Vachon (2001) state that there is an overwhelming trend to follow the chase strategy, i.e., adapting capacity to demand. The chase strategy requires planning the production rate of each line and a working calendar for each line months in advance. For the mid-term planning horizon, the workforce's flexibility and working time play a particularly important role (Sillekens et al. 2010). The production rate decision will have an impact on the manning required: the higher the production rate, the more people required to work with it.

Therefore, the flexibility to change production rates is limited by the ability to hire people and changes cannot be made too frequently.

Although JIT requires stability on demand (Monden 1994), demand changes are frequent. They can be due to changes in client requirements, to the global network that is being served, or due to different working schedules held by international clients. Moreover, the production rate cannot be changed too frequently since these changes affect the stability of the SC requirements, which might have a huge impact on the system performance (Bozarth et al. 2009).

Since each line (both assembly and component) has different demand requirements and production rates, a different working calendar has to be defined for all six lines. Therefore, factory working calendars are used to chase demand by adding extra shifts or new down days—a down day is a normal working day when the factory decides to stop production to help balance the production level and the demand level. Down days are used, for instance, to do extraordinary maintenance or workers training. Calendars should respect the working calendars pre-established by staff and external stakeholders such as trade unions. Therefore, a penalty on the addition or removal of extra working shifts should be considered.

Since plant flexibility is limited, minimum stockpiling is admitted mainly to prevent holiday "clashes". The way to ensure that the inventory does not rise very much is to establish objective stock levels at the end of any long holiday period. The product demand has to be satisfied by the production capacity. If a decoupling of production over buffers is possible, then buffers have minimum and maximum amounts of stock (Sillekens et al. 2010). The plant will stockpile for weeks, and even months ahead of the holiday period foreseen, but stock levels will have to be reduced at the end of the period with a given objective.

This quantity of stock, due to the stockpiling process, should be balanced among those products with larger demand. Although from a mathematical point of view it is not relevant which product is to be stocked (or should it be the cheapest), from a practical point of view it does not make sense to manufacture too many units of a given product and nothing of the rest (although the product is only produced to be stocked). There is a practical reason for that requirement: an unbalanced production will lead to an unbalanced supply. In terms of stock managers it is also shown up as a dislike to unbalanced shipping banks. Nor do they like to have too many units of those products with low demand, since the demand of those products might disappear unexpectedly.

3.1.2 6-month detailed production plans and 6-month material requirements plans

Once the 6-month capacity production plans have been accepted, detailed production plans and material requirement plans are required. Production plans will have to cope with transport requirements and will generate material requirements.

Due to the relatively high number of components and products being produced, the detailed production and stock levels of the products in each period will help us know if we will be able to cope with the problem.

Requirements have to be communicated to the entire SC so that each area can adjust its productive capacity. In the case study presented herein, the critical raw materials for several of the major engine components are purchased directly from international foundries working with long and variable supply times.

According to the user requirements, only the five major components (5Cs) are planned, and the rest are done using the company's ERP system that holds the whole BOM.

3.2 4-week operations planning (4WOP)

The 4-week operations plan must satisfy the requirements of the logistics department, but must also take into account the constraints that the production department defines. Both these departments have contradictory objectives and

Table 3 4WOP characteristics

	Procurement	Production	Distribution
Tasks	Ordering materials for short-distance suppliers	Engine production planning	Engine transport planning
	Material requirements planning	Detailed component production plans	Component transport planning
Objectives	Minimize raw material stock levels	Maximize production leveling	Maximize engine delivery fulfillment
		Minimize inventory faults	Minimize backlog costs
		Minimize set-ups costs	
Constraints	Working calendars	Safety stock level constraints	Working calendars
	FTL strategy	Maximum stock level limits	FTL strategy
	Truck and rack capacity	Max/min number of derivate products manufactured	Truck and rack capacity
		Daily production capacity	Demand fulfillment
		Availability of raw materials and components	
Decisions	4-week material requirements plan	4-week engine production plan	4-week transport plan
		4-week detailed component production plans	

different constraints, and the trade-off that usually occurs in real meetings has to be considered with the implemented model.

Using the same approach as for the 6MMP, Table 3 summarizes the case of the 4WOP and some of the characteristics considered.

In this case study, the 4WOP process generates three main plans:

1. 4-week transport plan aimed to minimize products and component shipping costs.
2. 4-week engine production plan and 4-week detailed component production plans with different objectives for each production line in an attempt to accomplish stability in one case and to cut setup costs for the others.
3. 4-week material requirements plan that aims to both schedule production quantities to short-distance suppliers and order shipping quantities to long-distance suppliers.

The overall objective is always said to minimize total costs; yet in general, these costs are unknown. The model was designed to hold them all. A parameter tuning was manually and heuristically performed in the implementation phase.

3.2.1 The 4-week transport plan

Transport planning is a fundamental task since the costs involved are substantial. The demand of each client, expressed in units per day with a 4-week horizon, is obtained from the company's ERP system.

In our case, each client has a different working calendar, and shipping calendars have to be calculated from them. Each client is different and backlogging has different costs for each one (e.g., it is not the same to stop a car assembly line than to delay the shipment of two units to the R&D department).

Trucks and containers have a different rack capacity depending on the client. Racks have a different capacity depending on the product. Although filling trucks might not be seen as a lean practice, the transport efficiency will require this practice. The FTL strategy (Ozdamar and Yazgac 1999), and its associated unit load constraints, generate the need to consider over-deliveries when serving before being requested in order to fill trucks. In practice, each client will accept different under-delivery or over-delivery levels. In this paper, this situation is named positive and negative backlogging.

3.2.2 The 4-week production and detailed production plan

As mentioned earlier, the system can be defined as a two-stage hybrid flow shop in which the second stage is a mixed model assembly line and the first stage involves multi-model production lines (Quadt and Kuhn 2008). This specific type of flexible flow shop with assembly operations, quoted for instance at Yokoyama (2008), does not sustain simple objetives. The objectives for the first stage are to reduce the number of setups, and to minimize inventory and production costs of various kinds (Garcia-Sabater and Vidal 2008). In the second stage, however, reaching a leveled production is the main objective, i.e., the MMAL problem (Bautista et al. 1996).

In our case, it also has to consider the transport plan. The integration of transport and production decisions into SCs has been the object of several papers and it is shown to be a difficult task (Cardos Carbonera and Garcia-Sabater 2006; Günther and Seiler 2009; Mula et al. 2010; Simpson and Erenguc 2001).

In the traditional approach, planning and scheduling are implemented sequentially. The production plan is determined before the actual scheduling (Lee 2002). In this case study, engine production planning should also be synchronized with component production scheduling due to the capacity limits at the inventory level. Each production line is characterized by its production rate and by its relatively long cycle times and high setup costs. Besides, the supply lead-time is measured in days or weeks for some components. Thus, coordination between planning and scheduling for the whole SC is critical.

In order to achieve this coordination, specific constraints for the different characteristics are to be considered. For instance, in the case of the assembly line the number of derivatives that may be simultaneously assembled on the engine line is limited. In the case of the 5C manufacturing line, the setup process on the components lines is not standard and requires different levels of manning depending on the urgency of the setup, and it holds sequence dependency. The inventory capacity between lines and at the shipping bank is limited. Alternative BOMs are possible depending on the availability of components.

The planning process will use the information supplied by the 6MMP process in the form of calendar and stock targets at the end of each planning period (i.e., the week).

3.2.3 The 4-week material requirements planning

Apart from some raw materials that arrive from long distance suppliers, the bulk of the purchased components come from European suppliers or from suppliers on a nearby industrial park. The European suppliers have a lead-time of around 4–7 days. Local suppliers might serve on the same day.

A 4-week purchase plan with daily periods is created to take into account the entire supply base. Depending on the supplier, a frozen period is established and some changes are not allowed.

3.3 The daily planning process

For years, the explicit and implicit constraints, objectives and goals of each team involved in the reception, production and delivery of materials were fitted in daily meetings by changing almost any part of the plan. Since plans were generated manually, this form of managing constraints and objectives was not a bad option, and anything could be changed if everyone agreed.

Yet if we intended to use an automatic planning system that considers such meetings, it could not be managed in the same way.

Now, constraints have to be explicit and should be given before the plan is to be made. To help the planning department staff deal with the other departments, the above-mentioned plans are transformed into a very short-term schedule for each section. Detailed engine production plan for the assembly line and a detailed transport plan for some suppliers and clients were generated to show the plans to help during the negotiation process. Table 4 offers the basic characteristics of the daily planning process.

It has to be pointed out that initially the purpose of the project was to create the detailed production plan for each and every line. Since that schedule required a huge quantity of non-yet available data (for instance, maintenance plans), this objective was eliminated.

Therefore, there is no model available to solve the daily planning process. However, considering the objectives and constraints in the daily planning process is necessary since the 4WOP model has to propose a schedule to be used to create detailed and definitive schedules for each line.

In general, objectives and constraints are considered at previous planning levels to ensure that solutions are executable at the next planning level. For instance, the sequence on the assembly line is done with a specific software that sequences the MMAL. This software has to be fed with information about the quantity of engines to be assembled. The 4WOP process creates a plan that can be easily transferred by considering the limitations of the number of derivatives (both minimum and maximum).

4 MILP model formulation for the 6-month master planning process

This section introduces the mathematical formulation for the 6MMP process as it has been modeled in this specific case.

Table 4 The daily planning process characteristics

	Procurement	Production	Distribution
Tasks	Ordering materials Reception planning Detailed load truck planning for procurement	Engine quantity definition	Detailed load truck planning for transport
Objectives	Minimize raw material stock levels Maximize truck fulfillment	Minimize set-ups costs	Maximize truck fulfillment
Constraints	FTL strategy Truck and rack capacity	Max/min number of product derivates manufactured Sequence dependence	FTL strategy Truck and rack capacity Demand fulfillment
Decisions	Daily detailed procurement plan	Daily detailed engine plan	Daily detailed transport plan

4.1 Basic assumptions

In our 6-month master plan, the horizon is divided into 25 time buckets of 1 week each. This was the original way of working and has been maintained. For each week, demand forecasts are known, although the latest periods are not complete neither fully reliable. The planners' main objective is to firstly generate a feasible calendar that includes production rates, number of working days and down days, and the number of extra shifts per week.

Capacity might lessen by adding new down days. Similarly, capacity might increase by adding new extra shifts to those already planned. The calendar and the production rate for each line are decided at a plant level. Therefore, our tool generates plans to assess the best combination, but it does not decide it.

Inventories and the BOM of each product are also known (using the company's ERP system), but only the data related with the main 5Cs components are considered. Stock levels are considered in two different ways. First, the stock level of each product has to be over a predefined safety stock level, although the available stock at the end of each period should be balanced between product types. This stock balance implies to keep a shipping bank (end product ready to be sent) as balanced as possible by keeping a similar run-out for each product type.

4.2 Notation

To mathematically formulate the problem, it is necessary to define the nomenclature presented in Tables 5, 6 and 7.

4.3 Objective function

The objective of the proposed model is to minimize total costs (1).

Table 5 Sets and indexes

i, $i1$, $i2$	Indexes for products (engines and components)
$E\epsilon\{E1\}$	Index for engine assembly line
$C\epsilon\{C1,\ldots,C5\}$	Index for components production lines
$\xi\epsilon\{E, C\}$	Index for production lines
t	Index for time (t = 1…T)
L_ξ	Set of products produced on line ξ

$$\min \left\{ \begin{array}{ll} \sum_t \sum_i C^Y_{i,t} \cdot \left(y_{i,t} - SS_{i,t}\right) & (1.1) \\ + \sum_t C^L_t \cdot \lambda_t & (1.2) \\ + \sum_t \sum_\xi \left(C^{ND}_{\xi,t} \cdot \left(n^{ND}_{\xi,t} - d^{ND}_{\xi,t} \right) + C^{ES}_{\xi,t} \cdot n^{ES}_{\xi,t} \right) & (1.3) \\ + \sum_t \sum_{i \in L_E} C^\Gamma_{i,t} \cdot \left(\gamma_{i,t} - \Delta\right) & (1.4) \\ + \sum_t^{\overline{\Lambda}} C^P_t \cdot \left(p^+_t + p^-_t\right) & (1.5) \end{array} \right\} \qquad (1)$$

The holding costs of inventory are only considered if the stock is over the safety stock level (1.1). Costs are different per product and per period, since the relevance of the over-stocks depends on both the product and the horizon.

However, inventory has to be controlled to keep a balanced shipping bank of each product, as mentioned previously. In order to do so, the value of the unbalanced shipping bank for each period, together with Constraint (4), has to be minimized. This is the purpose of Objective (1.2): to track and keep a leveled shipping bank among the different products.

Summation (1.3) holds to minimize the use of days and extra shifts. The parameters are tuned to prefer a normal day to an extra shift. Yet should staff wish to consider an extra shift, it can be added as a parameter.

Summation (1.4) attempts to create a leveled plan by minimizing the differences between the consecutive periods of the same plan. This is a basic objective in order to create and sustain a lean supply chain.

Summation (1.5) attempts to create plans that are as stable as possible in terms of the previous plans results. With p^+_t and p^-_t we intend to measure the maximum positive and negative deviation of the planned production on a given day compared against the previous plan.

Like most real problems, the problem presented herein is a multi-criteria one. We used a weighted criteria approach to reduce it to a single objective. The fine tuning of the so-called cost parameters will enable the creation of a plan that *satisfices* users.

Table 6 Parameters notation

T^{EST}	Number of consecutive weeks of production while maintaining a leveling
$C^{Y}_{i,t}$	Cost of holding a unit of *i* during week *t*
$C^{\Gamma}_{i,t}$	Cost of a non leveled plan for product *i* in week *t*
C^{P}_{t}	Cost of a non stable plan in week *t*
C^{L}_{t}	Cost of a non balanced shipping bank in week *t*
$C^{ND}_{\xi,t}$	Cost of a normal day in week *t* on line ξ
$C^{ES}_{\xi,t}$	Cost of an extra shift in week *t* on line ξ
$SM_{i,t}$	Maximum stock level of product *i* in week *t*
$SS_{i,t}$	Safety stock level of product *i* in week *t*
$SD_{i,t}$	Desired stock level of product *i* in week *t*
$D_{i,t}$	External demand of product *i* in week *t*
$Q_{i1,i2}$	Number of units of *i2* required to produce one unit of *i1*
LT_{i}	Lead-time of product *i*
$K_{\xi,t}$	Daily production capacity of line ξ in week *t*
$J^{ND}_{\xi,t}$	Number of normal days that line ξ is planned to work in week *t* in a previous plan
$J^{ES}_{\xi,t}$	Number of extra shifts that line ξ is planned to work in week *t* in a previous plan
$J^{MAXND}_{\xi,t}$	Maximum number of normal days that line ξ can work in week *t*
$J^{MAXES}_{\xi,t}$	Maximum number of extra shifts that line ξ can work in week *t*
$NS_{\xi,t}$	Number of shifts per working day on line ξ in week *t*
$RPL_{i,t}$	Scheduled quantity for receipt of product *i* in week *t* because of previous plans
$PX^{\tau-1}_{i,t}$	Planned production for product *i* in week *t* in a previous plan
Δ	Percentage that limits the production mix changes penalization
Ψ	Limiting percentage that defines if a product has low demand
$\overline{\Lambda}$	Latest period in which the whole planned capacity has to be used

4.4 Constraints

$$y_{i1,t} = x_{i1,t} + y_{i1,t-1} - D_{i1,t} + RPL_{i1,t} - \sum_{i2} \left(Q_{i1,i2} \cdot x_{i2,t} \right) \quad \forall i1, t \tag{2}$$

$$SS_{i,t} \le y_{i,t} \le SM_{i,t} \quad \forall i, t \tag{3}$$

$$y_{i,t} \ge (1 - \lambda_t) \cdot SD_{i,t} \quad \forall i, t \tag{4}$$

$$K_{\xi,t} \cdot w_{\xi,t} = \sum_{i \in L_\xi} x_{i,t} \quad \forall \xi,\ t < \overline{\Lambda} \tag{5.1}$$

$$\sum_{i \in L_\xi} x_{i,t} \le K_{\xi,t} \cdot w_{\xi,t} \quad \forall \xi, t \ge \overline{\Lambda} \tag{5.2}$$

$$w_{\xi,t} = J^{ND}_{\xi,t} + \frac{J^{ES}_{\xi,t}}{NS_{\xi,t}} + n^{ND}_{\xi,t} - d^{ND}_{\xi,t} + \frac{n^{ES}_{\xi,t}}{NS_{\xi,t}} \quad \forall \xi, t \tag{6}$$

Table 7 Variables notation

$y_{i,t} \in \mathbb{Z}^+$	Stock level of product *i* in week *t*
$x_{i,t} \in \mathbb{Z}^+$	Production of product *i* in week *t*
$r_{i,t} \in \mathbb{Z}^+$	Requirement of material *i* in week *t*
$\gamma_{i,t} \in \mathbb{R}^+$	Unleveled production of product *i* in week *t*
$p_t^+ \in \mathbb{R}^+, p_t^- \in \mathbb{R}^+$	Negative and positive production instability rate in week *t* in relation to previously planned production
$\lambda_t \in [0,\ 1]$	Percentage of the balanced stock level that indicates how far the worst product stock is from its desired level in week *t*
$w_{\xi,t} \in \mathbb{R}^+$	Working days in week *t*
$n_{\xi,t}^{ND} \in \mathbb{Z}^+$	Proposed new normal days in week *t*
$d_{\xi,t}^{ND} \in \mathbb{Z}^+$	Proposed new down days in week *t*
$n_{\xi,t}^{ES} \in \mathbb{Z}^+$	Proposed extra shifts in week *t*

$$n_{\xi,t}^{ND} - d_{\xi,t}^{ND} \leq J_{\xi,t}^{MAXND} - J_{\xi,t}^{ND} \quad \forall \xi, t \tag{7}$$

$$n_{\xi,t}^{ES} \leq J_{\xi,t}^{MAXES} - J_{\xi,t}^{ES} \quad \forall \xi, t \tag{8}$$

$$\gamma_{i,t} \geq \max\left(\Delta; \left|\frac{\sum_{\tau=t+1}^{t+T^{EST}} x_{i,\tau}}{\sum_{\tau=t+1}^{t+T^{EST}} \left(J_{E,\tau}^{ND} \cdot K_{E,\tau}\right)} - \frac{x_{i,t}}{J_{E,t}^{ND} \cdot K_{E,t}}\right|\right) \quad \forall i \in L_E, t < T - T^{EST} \tag{9}$$

$$x_{i,t} \leq PX_{i,t}^{\tau-1} \cdot \left(1 + p_t^+\right) \quad \forall t < \overline{\Lambda} \quad \forall i / D_{i,t} > \Psi \cdot K_{\xi,t} \tag{10}$$

$$x_{i,t} \geq PX_{i,t}^{\tau-1} \cdot \left(1 - p_t^-\right) \quad \forall t < \overline{\Lambda} \quad \forall i / D_{i,t} > \Psi \cdot K_{\xi,t} \tag{11}$$

$$r_{i2,t} = \sum_{i1} \left(Q_{i1,i2} \cdot x_{i1,t+LT_{i2}}\right) \quad \forall i2 \text{ with long lead-times } \forall t < T - LT(i2) \tag{12}$$

$$\sum_{\tau=1}^{t} r_{i,\tau} \leq \sum_{\tau=1}^{t} RPL_{i,\tau} \quad \forall i, t \leq LT(i) \tag{13}$$

The classical continuity constraints apply to the model (2). There are two origins for product consumption: external demand and internal demand (requirements from the engine assembly process). The second part of demand applies only to those components to be used for the engines on the assembly line. Therefore, it is not necessary to consider lead-times, which might be longer than 1 day, but no longer than 1 week.

For any engine and component, its inventory level should not be lower than the safety stock level (3). These safety stock levels differ per product and per period since they have to consider the forecasted demand of the product.

However, there are also other stock limits to be considered as a user might impose a limit in terms of:

- quantity for a given time (since it might expect change),
- run-out time (a user that does not wish to hold more than a given amount of days of demand).

These limits are defined before the model is to be launched. Then stock level limits take the form of a (lower and upper) bound constraint.

Another constraint to create acceptable plans is required: the need for balanced shipping banks (i.e., the amount of each end product in stock should be related with users' wishes). Then Constraint (4) is created. The system creates (according to product demand) a desired stock level, and we evaluate λ_t with Constraint (4) which informs how far the worst engine stock level actually is from its desired level.

Another typical constraint is the capacity constraint, which is usually an inequality. Planned production in the case we present herein has to equal planned capacity. The sum of engine production at any time has to equal the daily production rate multiplied by the number of working days for each line (5.1). Since the data for the latest demand periods are incomplete, Constraint (5.2) relaxes the constraint of producing at full capacity for these bucket periods.

Constraint (6) allows the evaluation of the capacity measured on production days. It considers that a new normal day $\eta_{\xi,t}^{ND}$ might be added or subtracted $d_{\xi,t}^{ND}$ and that new extra shifts might be added $\eta_{\xi,t}^{ES}$.

Constraint (7) limits the number of new normal days which might be added or subtracted, while Constraint (8) limits the number of extra shifts that might be added. Previously accepted extra shifts are not to be reduced with the model since it this is a plant decision taken elsewhere.

It is well-known that JIT systems require stability and leverage. The goal of having leveled plans is approached within this model by using Constraint (9) together with Objective (1.4). This constraint only applies to the engine line.

Production capacity is estimated with $J_{E,t}^{ND} \cdot K_{E,t}$. As Eq. (9) is nonlinear, Constraints (9.1) to (9.3) linearized it.

$$\gamma_{i,t} \geq \Delta \quad \forall i \in L_E, t < T - T^{EST} \tag{9.1}$$

$$\gamma_{i,t} \geq \left(\frac{\sum_{\tau=t+1}^{t+T^{EST}} x_{i,\tau}}{\sum_{\tau=t+1}^{t+T^{EST}} \left(J_{E,\tau}^{ND} \cdot K_{E,\tau} \right)} - \frac{x_{i,t}}{J_{E,t}^{ND} \cdot K_{E,t}} \right) \quad \forall i \in L_E, t < T - T^{EST} \tag{9.2}$$

$$\gamma_{i,t} \geq - \left(\frac{\sum_{\tau=t+1}^{t+T^{EST}} x_{i,\tau}}{\sum_{\tau=t+1}^{t+T^{EST}} \left(J_{E,\tau}^{ND} \cdot K_{E,\tau} \right)} - \frac{x_{i,t}}{J_{E,t}^{ND} \cdot K_{E,t}} \right) \quad \forall i \in L_E, t < T - T^{EST} \tag{9.3}$$

Constraint (9) allows a comparison of production rates to be made between 1 week and its T^{EST} consecutives. Constraint (9.1) neglects the evaluation changes of less than Δ. This constraint reduces enormously the calculation time without incorporating any significant variation on the result.

Constraints (10) and (11) help evaluate the stability of the plans deployed on previous days. These constraints only apply to those products with a demand over Ψ of the overall capacity considered. Products with low demand are not considered since product flow it is not largely affected.

As stated above, the implemented model has to create the material requirements for raw materials with long supply lead-times (12). These requirements are limited by the scheduled quantity for receipt within their lead-time (13).

4.5 6MMP parameter tuning and other implementation issues

Parameter tuning has been done using an iterative approach. Each time the problem has been solved, the management team has been asked to evaluate the solution by pointing out the characteristics of those results they did not like. Their comments have helped us create new constraints in some cases, but they were able to mainly change the parameters value.

Unexpectedly, inventory costs are not relevant for most products. The inventory level cost is translated to the plan through products and production lines limits. Inventory levels are bound or limited, and 6-month inventory costs are only relevant for those products with low demands.

In order to cover demand, planners define a desired stock level in some specific periods (e.g., for a post-holiday period). The plan has to adjust to such levels as much as possible. The objective related with this desired stock level is the most relevant of those related with inventory. Our model only considers the product with the lower run-out time for each period.

Another basic objective in the automotive industry is to reduce the nervousness between consecutive plans. Planners wish to see that previous plans are similar to the current plan. But, in fact, this only applied to products with high demand. Users agreed to consider penalties, but only for products whose demand is higher than 10% of the production capacity.

Stability between consecutive periods of a given plan is basic to implement JIT tools and techniques. Therefore, penalizing unleveled production was relevant, but only for engines with high enough demand and for neglecting variations of less than Δ of capacity (in our case, $\Delta = 5\%$ proved to be a good value for final users). Moreover, the incorporation of this parameter drastically reduced the computational effort without affecting the quality of the solution. Stability refers not only to consecutive periods. Constraint (9) allows a comparison to be made of production rates between 1 week and its T^{EST} consecutives (in our case, considering $T^{EST} = 3$ has proven adequate).

Moreover, Table 8 presents the values of the tuned costs and the hierarchy of all the objectives for planners. The latest column gives the range of the different summations in different resolutions. In order to understand the table, it has to be pointed out that in some cases the coefficients are null (i.e., the holding cost for high demand products).

The specific characteristics of the problem herein presented allow us to consider that the different problem objectives have different scales of magnitude. Each time that a new extra day or a new down day is added (or subtracted), hundreds of engines (very similar to each other) are (or not) to be produced. This decision greatly affects not only working calendars costs, but also the production and holding costs of the engines and components to be produced and stored. However, it has to be pointed out that the capacity consumed to produce one unit of each engine is the same as the others. When the decision on the working calendars is made, the rest of the problem has a different scale of magnitude, but, as mentioned, this is mainly due to the fact that each engine (although differing among types) is quite similar to other different type engines. Therefore, parameter tuning may be done on different scales

Table 8 Values of the cost and penalty parameters in the 6MMP model

Variable Name	Control (C) or decision (D) variable	Number of variables	Minimum value of the variable	Maximum value of the variable	Hierarchy of the objectives	Associated cost values	Range of objective values after resolution
$n^{ES}_{\xi,t}$	D	750	0	$J^{MAXES}_{\xi,t} \approx 3$	1	$C^{ES}_{\xi,t} \approx 10^3$	$[0 - 10^4]$
$n^{ND}_{\xi,t}$	D	750	0	$J^{MAXND}_{\xi,t} \approx 2$	2	$C^{ND}_{\xi,t} \approx 10^2$	$[0 - 5 \cdot 10^3]$
$p^+_t \& p^-_t$	C	50	0	1	3	$C^{P}_{t} \approx 10^1$	$[0 - 10^2]$
λ_t	C	25	0	1	4	$C^{\Gamma}_{i,t} \approx 10^1$	$[0 - 3 \cdot 10^1]$
$\gamma_{i,t}$	C	1,092	0	$K_{\xi,t} \approx 2,000$	5	$C^{\Gamma}_{i,t} \approx 10^{-4}$	$[0 - 5 \cdot 10^0]$
$y_{i,t}$	C	1,525	$SS_{i,t} \approx 400$	$SM_{i,t} \approx 4,000$	6	$C^{Y}_{i,t} \approx 10^{-5}$	$[0 - 1 \cdot 10^0]$

Table 9 Size of a given instance of the 6MMP

	Variables	Integers	Constraints	Non-zero	Density
6MMP	5,361	1,503	8,546	20,696	0.05%

of magnitude without affecting the overall result. This behavior cannot be expected when the products to be produced differ from each other by either using different capacities or having very different production or holding costs. In such cases, the parameter tuning process will probably become much more relevant and, therefore, standard multi-objective methods will have to be used to guarantee the structural validity of the problem.

4.6 6MMP results

6MMP was in fact used to coordinate with two domains, one of which is 4WOP. The other is the plant management staff dealing with the "calendar" problem: extra shifts, down days, production capacity. The plan has to take into account "soft" issues and information sources, such as expected transport strikes, union agreements and potential new clients. They need quick answers and many different alternative plans.

Since the 6MMP model is quite large (see Table 9), it is expected computational time is too long.

To cut this time, two paths have been followed. One has been used to avoid minimizing the objective function to the optimum one if not compulsory (e.g., relax Objective (1.4) using Constraint (9.1)).

The other has already been outlined and relates to the different users' needs. The 6MMP process was converted into a two-step one. In the first step, we were mostly interested in calendars (the capacity plan), while our aim with the second step (once calendars had been defined) was to reach the optimal production and operations plan.

This two-step strategy has been approached with the model that has been previously described with minor changes. In the first stage we consider only Objective (1.3) by multiplying the other objectives by 0, thus neglecting the values of their coefficients.

In the second stage we consider only Objectives (1.1), (1.2) and (1.4), while some objectives and constraints were added by assigning the value of zero to variables $\eta^{ND}_{\xi,t}$, $\eta^{ES}_{\xi,t}$, $d^{ND}_{\xi,t}$; by doing so, the calendar parameters (normal days and extra shifts) are made constant.

The purpose of the first stage is to help create a feasible calendar. The primary requirement is to solve the problem in real time to make the decision-making process easier. To go about this, Objectives (1.2), (1.4) and (1.5) are neglected by multiplying their summations by 0 for the objective function. This problem can be solved in 50 s using ILOG CPLEX 12.1 in a computer with an Intel Core2Duo 2.40Ghz processor, 4 GB RAM and Windows 7 as OS.

The same problem can be solved iteratively by adjusting the parameters (daily production capacity, limitations about calendars or desired stock level) that rely on

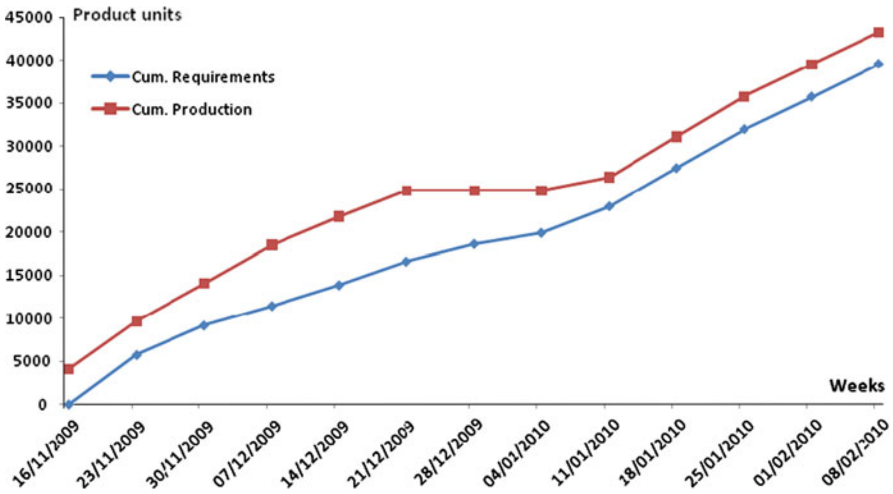

Fig. 3 Stockpiling and consumption using the 6MMP

top management issues. If required, a handful of calendars may become available at the end of the process. The plant's staff will decide the best feasible calendar and usually accepts the first result.

Once a feasible calendar has been accepted by the plant's staff, the second stage starts. Some parameters and variables are neglected or forced to be null to fix the accepted calendar. Then the model is again solved and the variables values $\{y_{i,t}, x_{i,t}, r_{i,t}\}$ are the plan we were looking for.

Each 6MMP model has a certain number of parameters, these being variables that are expressed for a given instance (the plan starting the second week of November 2009).

A result of a problem solved in November 2009 is shown in Fig. 3, where the Christmas stockpiling effect is easily seen.

As a result of this solution, stock levels for each particular product at the end of each week ($y_{i,t}$), together with the calendar, will be used to feed the 4WOP. The production plan is also introduced into the corporative ERP system to create the material requirements for the rest of the components, and variable $r_{i,t}$ helps the planner adjust the procurement plan.

5 Model formulation (4WOP)

5.1 Basic assumptions

To create short-term production plans, a 4-week horizon is divided into days. This was the original way of working, which has been maintained. The demand forecast for each day is known, and is almost certain. The 6MMP results give information about how many shifts are to be worked each day, the production rate that each line is going to reach and the inventory levels that have to be reached per product at the end of each week. The initial stock levels and the backlogs for each client and product (either positive or negative) are known.

The whole BOM is not considered as only the main 5Cs are relevant. Most products have alternative BOMs. The alternative BOM problem has been approached using the stroke concept presented in Garcia-Sabater et al. (2011) and in Maheut et al. (2012), which is similar to the task concept presented in Lang (2009) and Begnaud et al. (2009).

Our model generates a 6-week horizon plan, but shows only the first 4 weeks. The last 2 weeks are used only to guarantee model feasibility by anticipating major variations. The model generates not only production schedules at the two consecutive stages, but also defines inventory levels and determines the delivery of products and raw material requirements.

5.2 Notation

To help simplify the understanding of this paper, the notation of this model is that it is the same as that in the previous one, even though they do not refer to the same time buckets. However, some new parameters and variables have been introduced, as shown in Tables 10, 11 and 12.

It should be pointed out that different technologies lead to the various production lines producing completely different products. Therefore, several constraints have been required and created. Nevertheless, the main difference to be found lies between the engine assembly line and the other 5C's production lines.

Costs are only penalty parameters that allow to finely tune model performance. They should not be seen as real costs to be considered on any accountancy system. The variables used are presented in Table 12, except the otherwise noted variables, which are always positive integers.

5.3 Objectives

Creating a plan that satisfies the requirements of both the logistics and the production departments is a complicated task since each department has different goals. In some cases these are expressed as constraints and in others as objectives.

1. Maximize delivery performance
2. Maximize production stability
3. Minimize setup costs
4. Minimize inventory and production costs

Table 10 Sets and indexes

j	Index for clients
k	Index for strokes
$f, f1, f2$	Indexes for product families
PF_f	Set of products in product family f
AL_ξ	Set of product families produced on line ξ
Z_ξ	Set of strokes performed on line ξ

Table 11 Parameter notation

$D^*_{i,j,t}$	External demand of product i for client j in week t
$C^{BN}_{i,j,t}$	Cost of negative backlogging for a unit of i for client j on day t
$C^{BP}_{i,j,t}$	Cost of positive backlogging for a unit of i for client j on day t
$C^1_{f1,f2,t}$	Cost of the setup when $f1$ and $f2$ are produced on the same day t
$C^2_{f1,f2,t}$	Cost of having $f1$ and $f2$ produced on consecutive days t and $t + 1$
$CO_{k,t}$	Cost of realizing one unit of stroke k on day t
$SL_{\xi,t}$	Limiting the accumulated stock level for all the products manufactured on production line ξ on day t
$\underline{DER_t}$, $\overline{DER_t}$	Minimum/Maximum simultaneous number of derivatives that can be produced on day t on the engine assembly line
U_k	Use of resources when producing stroke k
W_i	Number of products i that must be held in their respective racks
V_j	Number of racks that must be held in a container or truck to client j
$SO_{i,k}$	Number of units of i that generates one unit of stroke k
$SI_{i,k}$	Number of units of i that requires one unit of stroke k
LT^*_k	Lead-time for stroke k
$LS_{i,j}$	Safety lead-time considered of product i for client j
$B_{i,j}$	Initial backlog of product i for client j
$RPL_{i,t}$	Scheduled quantity for the receipt of product i on day t
$FS_{i,t}$	Intended stock level of product i to be reached at the end of period t

Table 12 Variable notation

$v_{i,j,t} \in \mathbb{Z}^+$	Delivery of product i to client j on day t
$\mu_{i,j,t} \in \mathbb{Z}^+$	Numbers of racks of product i to client j on day t
$\varpi_{j,t} \in \mathbb{Z}^+$	Numbers of trucks or containers to client j on day t
$z_{k,t} \in \mathbb{Z}^+$	Number of strokes k on day t
$\beta^+_{i,j,t} \in \mathbb{Z}^+$	Positive backlog of product i for client j on day t
$\beta^-_{i,j,t} \in \mathbb{Z}^+$	Negative backlog of product i for client j on day t
$\chi_{i,t} \in \{0,\ 1\}$	=1, if product i is produced on day t (0, otherwise)
$\pi_{f,t} \in \{0,\ 1\}$	=1, if product family f is produced on day t (0, otherwise)
$\theta^1_{f1,f2,t} \in \{0,\ 1\}$	=1, if product families $f1$ and $f2$ are to be produced on day t (0, otherwise)
$\theta^2_{f1,f2,t} \in \{0,\ 1\}$	=1, if product families $f1$ and $f2$ are to be produced on day t and $t + 1$ (0, otherwise)

The overall objective is to minimize the total costs, although those costs are generally unknown. The model was designed to hold them all, and parameter tuning was heuristically performed in the implementation phase. The whole objective function is presented in (13).

$$\min\left\{\begin{array}{ll} \sum_t\sum_i\sum_j\left(C^{BN}_{i,j,t}\cdot\beta^-_{i,j,t}+C^{BP}_{i,j,t}\cdot\beta^+_{i,j,t}\right) & (13.1)\\ +\sum_t C^L_t\cdot\lambda_t & (13.2)\\ +\sum_t\sum_i C^\Gamma_{i,t}\cdot(\gamma_{i,t}-\Delta) & (13.3)\\ +\sum_t\sum_k CO_{k,t}\cdot z_{k,t} & (13.4)\\ +\sum_{t<T}\sum_{f1}\sum_{f2}\left(C^1_{f1,f2,t}\cdot\theta^1_{f1,f2,t}+C^2_{f1,f2,t}\cdot\theta^2_{f1,f2,t}\right) & (13.5)\\ +\sum_t\sum_i C^Y_{i,t}\cdot\left(y_{i,t}-SS_{i,t}\right) & (13.6) \end{array}\right\} \qquad (13)$$

The objective is a multi-criteria one. Moreover, we decided to consider a simple weighted schema with penalty weights defined to generate solutions to fulfill the client's requirements.

The objective of optimizing delivery fulfillment was modeled by Summation (13.1) in an attempt to minimize both the positive (the classical) and negative (serving in advance) backlogging costs. Backlogging costs differ depending on the product, the client and the time when backlogging exists.

With Summation (13.2), the objective to maintain the plan established at the 6-month level (6MMP) is expressed as an attempt to reach the intended stock level.

Summation (13.3) is used to maximize the equilibrium at the production levels of the consecutive periods for each product in order to leverage production, even if demand is not stable.

Summation (13.4) enables the selection of the cheapest possible alternative BOM. The costs of strokes have been defined so the model tends to select the preferential option, if available.

To consider the minimization of setup penalties, a specifically designed method has been implemented and is expressed in Summation (13.5). Components have been grouped into families. Plans are penalized if two different families are produced on the same component production line on the same day or on consecutive days. This way models the setup issue with enough quality and simplifies the whole sequencing process. This approach generates a feasible schedule and avoids the complexity involved in setting a sequence and having to evaluate it.

Finally, Summation (13.6) represents the objective of minimizing the inventory costs. From a realistic viewpoint, total stock levels will never be reduced since the production rate is fixed, as is demand. Inventory costs are used to keep the inventory as balanced as possible by penalizing those products with low demand or those that are going to disappear. Moreover, the model applies a penalty only for stocks over the safety stock levels.

5.4 Constraints

The constraints of the model are presented in this section.

$$SS_{i,t} \le y_{i,t} \le SM_{i,t} \quad \forall i, t \tag{14}$$

$$\sum_{i \in L_\xi} y_{i,t} \le SL_{\xi,t} \quad \forall \xi, t \tag{15}$$

$$y_{i,t} \ge (1 - \lambda_t) \cdot FS_{i,t} \quad \forall i, t \tag{16}$$

$$x_{i,t} = \sum_k \left(SO_{i,k} \cdot z_{k,t-LT_k^*} \right) \quad \forall i, t > LT_k \tag{17}$$

$$r_{i,t} = \sum_k \left(SI_{i,k} \cdot z_{k,t} \right) \quad \forall i, t \tag{18}$$

$$y_{i,t} = y_{i,t-1} + x_{i,t} + RPL_{i,t} - r_{i,t} - \sum_j v_{i,j,t} \quad \forall i, t \tag{19}$$

$$\sum_{k \in Z_\xi} \left(U_k \cdot z_{k,t} \right) = K_{\xi,t} \quad \forall \xi, t \tag{20}$$

$$\beta^+_{i,j,0} - \beta^-_{i,j,0} - \sum_{t=1}^{LS_{i,j}} D^*_{i,j,t} = B_{i,j} \quad \forall i, j \tag{21}$$

$$\beta^+_{i,j,t} - \beta^-_{i,j,t} = \beta^+_{i,j,t-1} - \beta^-_{i,j,t-1} - D^*_{i,j,t+LS_{i,j}} + v_{i,j,t} \quad \forall i, j, t \tag{22}$$

$$W_i \cdot \mu_{i,j,t} - v_{i,j,t} = 0 \quad \forall j, t \tag{23}$$

$$V_j \cdot \varpi_{j,t} - \sum_i \mu_{i,j,t} = 0 \quad \forall j, t \tag{24}$$

$$\gamma_{i,t} \ge \max\left(\Delta; \left| \frac{x_{i,t}}{K_{E,t}} - \frac{x_{i,t-1}}{K_{E,t-1}} \right| \right) \quad \forall i, t / i \in L_E \tag{25}$$

$$x_{i,t} \le \left(K_{\xi,t} + 1 \right) \cdot \chi_{i,t} \quad \forall i \in L_E, t \tag{26}$$

$$\underline{DER_t} \le \sum_{i \in L_E} \chi_{i,t} \le \overline{DER_t} \quad \forall t \tag{27}$$

$$\sum_{i \in PF_f} x_{i,t} \le \left(K_{\xi,t} + 1 \right) \cdot \pi_{f,t} \quad \forall f \in AL_C, t \tag{28}$$

$$\pi_{f1,t} + \pi_{f2,t} - \theta^1_{f1,f2,t} \le 1 \quad \forall (f1, f2) \in AL_C, \forall t \tag{29}$$

$$\pi_{f1,t} + \pi_{f2,t+1} - \theta^2_{f1,f2,t} \le 1 \quad \forall (f1, f2) \in AL_C, \forall t < T \tag{30}$$

$$\pi_{f1,t+1} + \pi_{f2,t} - \theta^2_{f1,f2,t} \le 1 \quad \forall (f1, f2) \in AL_C, \forall t < T \tag{31}$$

The stock constraints are (14) and (15). For any product and component, inventories should not exceed the storage capacity at any time, and ought not to be less than the defined safety stock level. However, these constraints might be relaxed if the problem has no available solution.

Each production line has a specific limited storage capacity. Constraint (15) limits the overall stock capacity of each production line separately.

Constraint (16), together with Objective (13.2), allows the coordination of the 6-month master plan and this 4-week operation plan through inventory levels. The $FS_{i,t}$ value is the stock that the 6MMP predicts for the end of each week period. The desired $FS_{i,t}$ stock level is to be reached at the end of the week.

The main peculiarity of the model presented in this paper is the use of the stroke concept to plan the operation. The stroke concept (Garcia-Sabater et al. 2011) allows the introduction of an alternative BOM. Each stroke represents any operation that transforms a series of products ($SI_{i,k}$) into another series of products ($SO_{i,k}$). Each product i might be produced using one stroke k or more. Therefore, the quantity of product i to be produced is a multiple of the stroke that produces it by considering the process lead-time, which is reflected as Constraint (17).

Furthermore, the requirements and purchases that have to be communicated with the appropriate lead-time are evaluated with $r_{i,k}$ using Constraint (18) and the stroke concept.

The classical continuity Constraint (19) holds for manufactured units.

The production capacity constraints are expressed as Constraint (20). The total production on each line should equal capacity, since they are typical assembly lines. So, they should work at the predicted takt time during the production period.

The FTL strategy means that the backlog constraints in this model are also special. Backlog is usually considered as a delay. When racks and containers are to be filled completely, a negative backlog is required. The continuity constraint applies in Constraints (21) and (22).

The units to be sent should be a multiple of the capacity of the rack that is going to hold them, as expressed in Constraint (23). Then the number of racks to be sent to a single client should fill the truck capacity, as in Constraint (24).

The purpose of Constraint (25) is to leverage the relative production quantity of the different types of engines between consecutive days. As Constraint (25) is nonlinear, we propose Constraints (25.1), (25.2) and (25.3) to linearize the constraint.

$$\gamma_{i,t} \geq \Delta \quad \forall i,t/i \in L_E \tag{25.1}$$

$$\gamma_{i,t} \geq \left(\frac{x_{i,t}}{K_{E,t}} - \frac{x_{i,t-1}}{K_{E,t-1}} \right) \quad \forall i,t/i \in L_E \tag{25.2}$$

$$\gamma_{i,t} \geq -\left(\frac{x_{i,t}}{K_{E,t}} - \frac{x_{i,t-1}}{K_{E,t-1}} \right) \quad \forall i,t/i \in L_E \tag{25.3}$$

Constraint (25) applies only to those products produced on assembly line ($\xi = E$). Since we are not interested in reaching an absolute balancing level to reduce the computational time, differences of less than Δ are not penalized.

With Constraint (26), we know if product i is produced on day t. We only consider the engines assembled on the assembly line.

The number of simultaneous engine derivatives scheduled on the engine assembly line for a given day influences assembly line management complexity.

Production managers asked to limit that number; the way to do this is shown in Constraint (27). Availability of a minimum number of derivatives was requested by the plant's staff. In fact, the case of a minimum and maximum number of derivatives is one of the ways the system has to coordinate with the daily production plan since it blindly incorporates some other physical constraints.

With Constraint (28), we know if product family f is produced on day t. Constraint (29) indicates if two families are scheduled on a given day. Constraints (30) and (31) do the same for consecutive days. Figure 7 in the implementation section provides a better understanding of our approach's sequencing capability.

5.5 4WOP parameter tuning and other implementation issues

As in 6MMP, parameter tuning was reached after an iterative process, where users' needs, constraints and objectives were considered and implemented.

To set backlogging costs, they were classified into two different levels: high and low. Backlogging costs (both positive and negative) differ per product, client and period. Basically, users consider that low demand products are less relevant than high demand products; assembly line clients are more relevant than spare parts clients; finally, it is not the same planning to not serve tomorrow than planning to not serve next week. The nearest backlog is almost sure and difficult to explain, while the farthest remains unsure (demand and production circumstances might prevent it); in any case, a warning can be launched to the client.

$FS_{i,t}$ is the stock at the end of the period that has been calculated by the 6MMP model. Due to the delivery process, it is quite feasible that stock is over the forecasted level at the end of the week; therefore, the purpose of the objective is to regularly maximize the approach to that level for all products. More specifically, each day does not have a positive $FS_{i,t}$ value, but only those at the end of the week (the bucket time period in the 6MMP model).

As with the 6MMP model, stability between the consecutive periods of a given plan is basic to implement JIT tools and techniques. Once again, we penalized unlevelled production, but only for engines with high enough demand by neglecting variations with less than Δ of capacity (in our case, $\Delta = 5\%$ proved a good value for final users).

In 4WOP, we consider alternative ways to produce the same product (mainly engines) and the cost system designed to make this decision simple. The stroke whose priority is to produce the engine has a null cost, and the other alternatives have a cost which, although positive, is much lower than the backlogging costs for the same product.

Setup costs are considered only on some component lines. In order to create feasible plans a reasonable computational time, components were grouped into families and the objective was to reduce the number of setups to a minimum. Cutting setup costs is the most relevant objective for each manufacturing line.

Table 13 presents approximate values for indices, variables and parameters to help readers understand the hierarchy of objectives, and weights are given to each variable.

Table 13 Values of the cost and penalty parameters in the 4WOP model

Decision variable	Control variable (C) or decision variable (D)	Number of variables	Minimum value of the variable	Maximum value of the variable	Hierarchy of the objectives	Associated cost values	Range of objective values after resolution
$\beta^{-}_{i,j,t}$	C	22,876	0	144	1	$C^{BN}_{i,j,t} \approx 10^1$	$[0 - 10^5]$
$\beta^{+}_{i,j,t}$	C	22,876	0	144	2	$C^{BP}_{i,j,t} \approx 10^0$	$[0 - 2 \cdot 10^5]$
$\theta^{1}_{i1,i2,t}$	C	13,552	0	2	3	$C^{1}_{\xi,t} \approx 10^2$	$[0 - 7,5 \cdot 10^3]$
$\theta^{2}_{i1,i2,t}$	C	13,552	0	2	4	$C^{2}_{\xi,t} \approx 10^0$	$[0 - 1,5 \cdot 10^2]$
λ_t	C	42	0	1	4	$C^{\Gamma}_{i,t} \approx 10^2$	$[0 - 4 \cdot 10^2]$
$\gamma_{i,t}$	C	1,708	0	$K_{\xi,t} \approx 2,000$	5	$C^{\Gamma}_{i,t} \approx 10^{-2}$	$[0 - 2 \cdot 10^1]$
$z_{k,t}$	D	1,900	0	$K_{\xi,t} \approx 2,000$	6	$C^{S}_{k,t} \approx 10^{-5}$	$[3 \cdot 10^1 - 4 \cdot 10^1]$
$y_{i,t}$	C	1,708	$SS_{i,t} \approx 400$	$SM_{i,t} \approx 4,000$	6	$C^{Y}_{i,t} \approx 10^{-4}$	$[0 - 1 \cdot 10^1]$

Table 14 Size of a given instance of 4WOP

	Variables	Integers	Constraints	Non-zero	Density
4WOP	136,657	53,404	120,095	1,540,270	0.017%

The previously commented specific problem structure can be seen in the leveling objective. The cost of an unleveled plan (or an unbalanced shipping bank) cannot be acquired from any database, and it is not relevant to compare it with the cost of having a new extra-shift. The plan has to be leveled to ensure its feasibility when produced on the assembly line. In fact, many physical constraints are hidden when the plan is leveled, but they can arise otherwise. However, it is not necessary to have an exact value of these costs. What is more, the optimal plan, no matter how easy it is to reach, is not necessary to acquire a good plan. Furthermore, low demand products should not be leveled at all. Therefore, costs are evaluated for each product and for each day depending on their forecasted demand. Products with demand lower than 5% of the available planned capacity have no costs relating to their unleveled production. This feature allows the system to work without being retuned when demand changes.

5.6 4WOP results

The 4WOP model is executed with a 6-week horizon, despite it showing only 4 weeks with a daily review period. Table 14 presents the data for an execution done in November 2010.

4WOP's resolution time (using ILOG CPLEX 12.1 on the same computer described above) is long. For the example used, the gap obtained was 2.76% after a 1-min run. To obtain a gap of 0.15%, a 10-min run was needed, which cannot be improved since the computer it was executed in went out of memory. It has to be said that bounds and gaps were calculated by the optimization tool.

After analyzing the results of these solutions, it can be stated that the obtained solution, with a gap of 2.76%, was inadequate. The delivery transport part of the solution with this gap could not be used. Figures 4 and 5 illustrate the large differences between the solution with a gap of 2.76%, which was clearly better in terms of backlogging given the solution with a gap of 0.15%.

When comparing Figs. 4 and 5, and the reality needs, the short term is seen to really matter. This feature has been transmitted to the model by cutting the cost of stocks and backlogging from the final period.

The transport optimization sub-problem (following the FTL strategy) has proved a very hard one. In fact, the problem is a difficult combinatorial problem; the period considered 12 clients (which means 12 trucks to be filled), and each client was buying between 5 and 12 engine derivatives.

At this point of the paper, we have to state that one of the main difficulties arising during the implementation process was the use of non-state-of-the-art solvers to solve the problem since the company did not buy the full license. Therefore, the computational time became too long. The user had to balance solution quality and

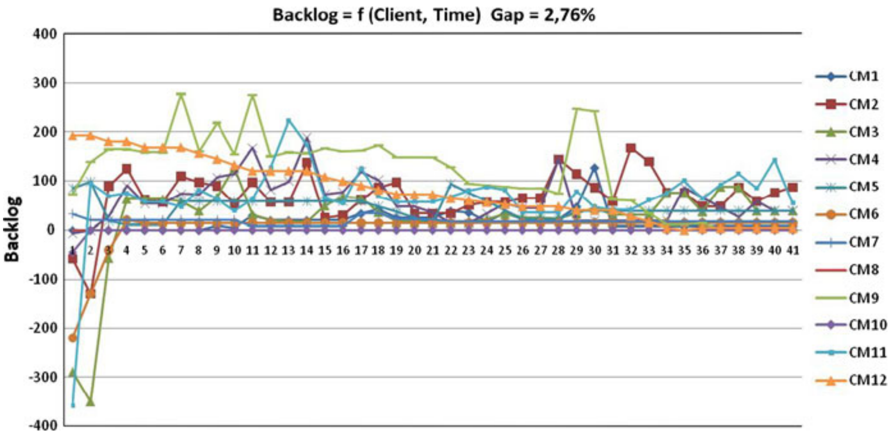

Fig. 4 Positive and negative backlogs with a gap of 2.76%

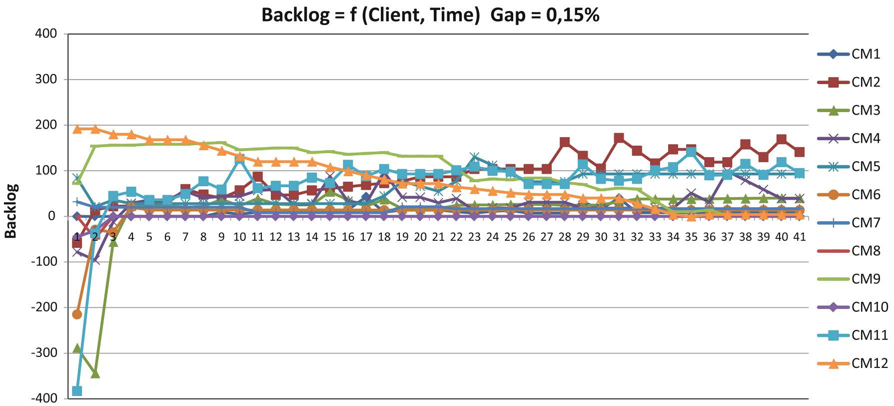

Fig. 5 Positive and negative backlogs with a gap of 0.15%

time performance by looking at the delivery plan and the gap obtained. He had to choose between two different strategies: to lengthen the resolution time or to use a heuristic deployed in Puig-Bernabeu et al. (2010) to create a feasible delivery plan to accept the created production plan.

The 4WOP model not only solves the delivery problem, but also production scheduling both for the assembly line and the 5C lines. On the assembly line, we need to ensure that the number of produced simultaneous derivatives (product types) is limited. Figure 6 presents these results and also shows how high demand products are produced daily, while the rest are evenly spread throughout the horizon.

The scheduling on the component lines is also defined in the 4WOP model. Figure 7 presents the schedule (using a gantt chart) for the cylinder head manufacturing line. The generated schedule allows the buyer to check if the raw material will become available.

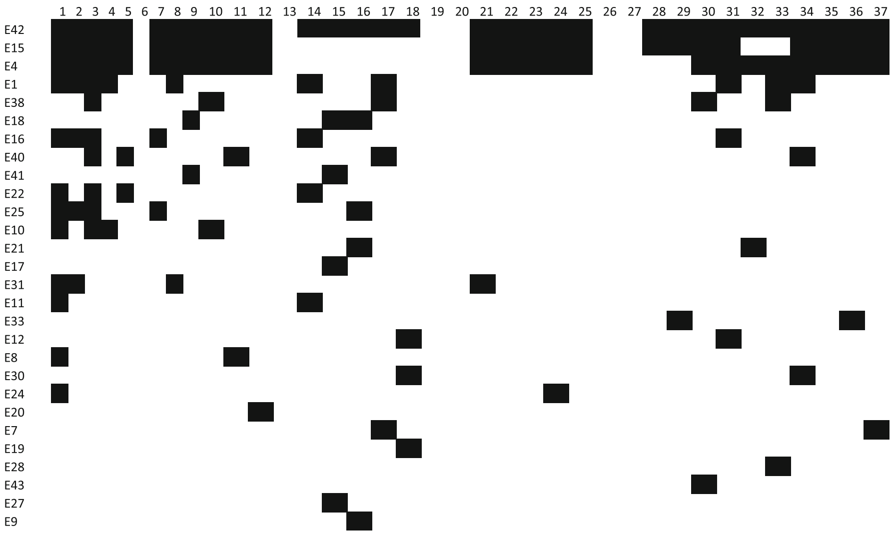

Fig. 6 Derivative presence for each within the horizon for each day

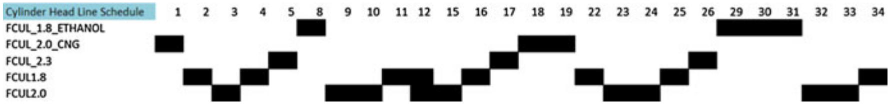

Fig. 7 Gantt chart for the Cylinder Head Line

Figures 5, 6 and 7 show how the same mathematical programming model has been able to plan delivery, assembly line production, and production on the components line. Moreover, since material requirements are derived from these calculations, it can be said that a supply chain planning problem is solved.

6 The advanced planning and scheduling implementation process

6.1 The modeling and implementation process

The analysis of the problem (and its modeling) started in May 2008. The first step was to understand how they were processing the information to create plans. The original process was quite iterative and based on the intensive use of separate spreadsheets. These spreadsheets included many colored conditional formatted cells, which allow users to both transmit and check the information gathered and created.

Evidently, the company has its own ERP system. However, working with it as a production planner has been proved somewhat difficult. Moreover, and as usual, the company's ERP system did not offer the possibility of including all the parameters required to generate “easy to use” plans. In some cases, it was simply proved too complicated to upload the information which is easily processed with spreadsheets.

Our approach to the modeling process was based on interviews held with the different users of the planning tools and with stakeholders to create a reliable solution. From their definition of the problem, the initial models were created. These models served as a basis to develop a three-party contract (a consultancy company, our research group and the client). Once we started to work with real data, the models started to change in an iterative process.

It is worth stating that during the fall of 2008 (4 months after starting the project), a global crisis arose. It allowed us to do a genuine sensitivity analysis since the models had been thoroughly tested for 9 months (October 2008–May 2009). One positive aspect also appeared: the users realized that they needed a tool to help them overcome the new and unstable environment that had emerged as a result of this crisis.

On the other hand, the need for models that take stability into account became relevant. It is well-known that lean environments require stability (Monden 1981). Before today’s crisis, this stability came directly from the demand data. Yet during the above-mentioned critical period, demand was anything but stable. This led to the need to synchronize models and to create stability variables, constraints and objectives.

Once the models were properly running, data such as costs or bounds were lacking. The implementation process included learning the best way to introduce costs, planned activities, critical limits and other apparently minor features.

One of the main aspects learnt was the need to always generate a plan, even if the original data are not feasible with the models above presented. To do so, an algorithm that relaxes constraints one by one was created, and once a solution was found, it was attached together with a message reporting the exact constraints that had been relaxed to allow the user to modify the data.

6.2 APS web-based description

This system has been deployed together with everis *SLU*, a Spanish consultancy company. This firm carried out the development process of the information system. The system not only includes the models presented herein, but also other features related with SC activities.

The task of creating the models and of implementing them using Java has been performed by the authors. We should point out that we have used *freemaker* and *JExcel* libraries.

The web-enabled APS runs outside the official ERP system. To obtain data from it and to generate a parallel database that stores the official data from the company and the rest of parameters that need to be used, specific connections were created. Users interact with the software by using standard browsers (to activate and to input data) and spreadsheets (to analyze and to use the results).

The so-called APS consists in four basic modules: DAL module, XML module, Solver module and Excel Module. The XML module retrieves information from the database and the company’s ERP system, and then transforms them into XML files.

The solver module reads the XML files and solves the models. The solution is sent to the XML Module that generates the solution files. Both the data and results are stored in the DAL module. The Excel Module is used to generate XML files that are to be opened with standard MS Excel©.

6.3 The information flow between models and with other functions of the company

The given model has been developed to be implemented in an engine manufacturing plant. At this point, it should be clear that our proposal considers two models: 6MMP and 4WOP. The 6MMP model is solved with two different pieces of data with a view to obtaining different results: with the first execution, it calculates a feasible calendar, while it calculates a 6-month production plan in just weeks with the next one.

In order to maintain consistent results, the different plans should be related with the other results/plans in three dimensions (hierarchy, domain and temporal). Figure 8 represents the relations among plans. Variables from other plans (from both previous executions and previous stages) are converted into parameters in subsequent models.

In our case study, integration of the different models has been done using constraints that limit the "autonomy" of each decision level. This is done downwardly (for instance, limiting the changes in the schedule with calendars parameters and production rate $K_{\xi,t}$ to the 6-month plans), and upwardly (i.e., manually including new constraints in the 6MMP model, such as limiting the

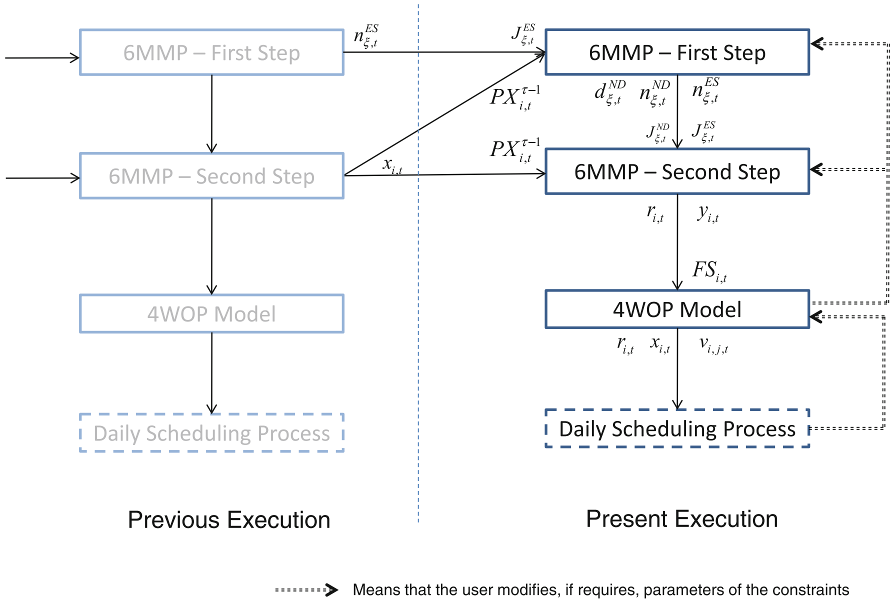

Fig. 8 Planning hierarchy

number of derivatives with Constraint (27) or limiting raw material availability in specific periods, if necessary).

The second integration level is business functions integration, which allows business functions to relate to each other. In our case study, this limitation is easily seen since our approach integrates the mathematical objectives and constraints into a single model. This integration is slightly more difficult to perform since objectives have to be counterbalanced and constraints are, in some cases, not compatible. Besides, it is far more difficult to solve because the number of integers and binary variables is quite high.

Finally, the models need to relate to the previous decisions (temporal dimension). This integration is considered with the parameter $PX_{i,t}^{\tau-1}$. This data has been specifically considered into the APS. Stability is not only a matter of planning stable plans; indeed, today's plan has to be similar to the plans of previous days. This concept is basic in the automotive sector and, in fact, there are specific performance measurements that are used only to evaluate stability. This is mainly justified by the fact that the SC cannot, or finds it difficult to, respond to major changes in production levels (Hüttmeir et al. 2009).

The so-called Intended Stock $FS_{i,t}$ helped coordinate 6MMP with 4WOP since it was (together with limited capacity) the relation that states what is to be produced by looking at the future beyond the first 4 weeks.

6.4 Some other considerations

A specific and highly relevant problem that had to be faced (to receive software users' approval when their job was to be substituted) was well managed by the team leader who prepared and waited until the person in charge of the job was about to retire. Turbulence due to the current crisis, with quick and unnoticed changes in demand, also revealed that the standard way of managing plans was no longer useful.

To avoid resistance from the white collar workers who were going to be replaced in the new working system, the APS was implemented by using standard interfaces, such as an Internet browser and an Excel spreadsheet. These interfaces allowed users to continue doing the same kind of activities they did before the Advanced Planning and Scheduling tool was developed. The use of the different Java TM APIs that integrate MS Excel with XML, plus other tools that easily modify the model syntax without having to generate new program files, has proved very interesting.

In order to implement an efficient system that is approved by planners, the system was validated by using a step-by-step approach. Mathematical models, which are at the core of the system, have been created in various spin-offs to cautiously respond to the approach of the different departments involved.

7 Conclusions

The models presented in this work are part of a more extended APS which was created to help the Supply Chain and Operations Activity in a real engine factory that mechanizes main engine components and assembles them into engines to then deliver them to more than 10 clients, each with its specific requirements.

Although the work presented herein is very practical, as a case study should be, the model development is useful at a theoretical level thanks to the constraints, linkages and coordination methods that appeared. Moreover, we present models that integrate production with transport planning by taking into account the requirements of an industry which is highly involved with JIT production practices.

The problem has been modeled as mixed integer linear programming models. At a practical level, the most relevant improvements in the plant after implementation are:

- The complexity of the operations planning process can be handled at the client level of detail.
- The complexity of the operations planning process can be handled at a deeper level of detail by considering the sequence-dependent setups on production lines, material supply, alternative BOMs and other scheduling issues.
- Freight issues, such as FTL, are explicitly considered in the production planning process.
- Although stock levels have not been reduced as limits (upper and lower), but are fixed by the management staff, the inventory is better balanced; therefore, the number of stock outs is lower.
- The speed of the planning process has improved considerably. The number of people involved in repetitive calculations has been cut from 4 to 2, who now focus on improving data accuracy activities.
- The data capturing process has been automated, the number of rescheduling process has been reduced, while plans' stability has improved.
- A better (and more stable) use of production and maintenance workers has also been achieved since the nervousness of plans (together with the nervousness of planners) has also diminished.

It is worthwhile pointing out some difficulties which arose during the project and can be extended to other projects:

- Difficulties in capturing requirements to design a tool when the information source is people who know that once they have "delivered" their knowledge, they will have to be "at best" moved to a new place in the company.
- Inaccuracy of data when these data (despite being in the corporative ERP) have not been used for a long time (for instance, the alternative BOM).
- Difficulties in obtaining a specific and "a priori" definition of constraints and objectives.
- Relevance of non-standard criteria (such as plan stability, production leverage or balanced shipping banks), together with the lack of relevance of classical objectives such as inventory holding costs.
- Difficulties to ensure the structural validity of the models because of the discrepancy between what planners said they wanted, what the real interest was and what the models were able to represent.

Finally, we wish to stress the idea that the recent advances in MILP resolution time (better hardware and much better software) have helped develop models that consider almost every characteristic of a real problem. As a pitfall, we can state that most users do not understand why they should buy this software as they do not understand what is does.

A future research line would be to develop algorithms that solve the problem without the need for state-of-the-art solvers. This algorithm would allow the use of these comprehensive models in companies which will not pay solvers.

Together, as a future research activity, a more data-resilient model and a resolution procedure are to be built. The model presented in this paper assumes that the data are accurate and that the plan will be executed. Yet in real systems, from time to time data are either not accurate or the reality does not render the model feasible. Providing users the ability to know which data (demand, stocks, production rates, etc.) is inaccurate would be the next good step to take.

Acknowledgments The work described in this paper has been partially supported by the Ministerio de Ciencia e Innovación del Gobierno de España within the Program de "Proyectos de Investigación Fundamental No Orientada through the project "CORSARI MAGIC DPI2010-18243″ and by the Universitat Politècnica de València, through the Project PAID-05-2010-2741. Julien Maheut holds a Val I + D grant funded by the Generalitad Valenciana (Regional Valencian Government, Spain) (Ref. ACIF/2010). The authors wish to thank three anonymous reviewers for their comments which have greatly improved the paper. They also wish to thank the people at the factory and at the IT consultancy firm for their continuous support and encouragement.

References

Bautista J, Companys R, Corominas A (1996) Heuristics and exact algorithms for solving the Monden problem. Eur J Oper Res 88(1):101–113

Begnaud J, Benjaafar S, Miller LA (2009) The multi-level lot sizing problem with flexible production sequences. IIE Trans 41(8):702–715

Bilgen B, Günther HO (2009) Integrated production and distribution planning in the fast moving consumer goods industry: a block planning application. OR Spectr 32(4):927–955

Boysen N, Fliedner M, Scholl A (2009) Level scheduling for batched JIT supply. Flex Serv Manuf J 21(1–2):31–50

Bozarth CC, Warsing DP, Flynn BB, Flynn EJ (2009) The impact of supply chain complexity on manufacturing plant performance. J Oper Manag 27(1):78–93

Cardos Carbonera M, Garcia-Sabater JP (2006) Designing a consumer products retail chain inventory replenishment policy with the consideration of transportation costs. Int J Prod Econ 104(2):525–535

Caridi M, Sianesi A (1999) Trends in planning and control systems: APS—ERP integration. In: Mertins K, Krause O, Schallock B (eds) Global production management. Kluwer, Dordrecht

Chen IJ (2001) Planning for ERP systems: analysis and future trend. Bus Process Manag J 7(5):374–386

Chern CC, Hsieh JS (2007) A heuristic algorithm for master planning that satisfies multiple objectives. Comput Oper Res 34(11):3491–3513

Choi TY, Hong Y (2002) Unveiling the structure of supply networks: case studies in Honda, Acura, and DaimlerChrysler. J Oper Manage 20(5):469–493

Chung SH, Snyder CA (2000) ERP adoption: a technological evolution approach. Int J Agile Manage Syst 2(1):24–32

David F, Pierreval H, Caux C (2006) Advanced planning and scheduling systems in aluminium conversion industry. Int J Comput Integr Manuf 19(7):705–715

Drexl A, Fleischmann B, Günther HO, Stadtler H, Tempelmeier H (1994) Konzeptionelle Grundlagen kapazi tätsorientierter PPS-Systeme. Zeitschrift für betriebswirtschaftliche Forschung 46:1022–1045

Dudek G (2004) Collaborative planning in supply chains. A negotiation-based approach. Springer, Berlin, p 2004

Fleischmann B, Meyr H (2003) Planning hierarchy, modeling and advanced planning systems. Handb Oper Res Manage Sci 11:455–523

Garcia-Sabater JP, Vidal P (2008) El problema de la programación del lote económico del ELSP: Una revisión de la literatura. X Congreso de Ingeniería de Organización 1:1–8

Garcia-Sabater JP, Maheut J, Marin-Garcia JA (in press) A new formulation technique to model materials and operations planning: the generic materials and operations planning (GMOP) problem. Eur J Ind Eng

Günther HO, Meyr H (2009) Supply chain planning and advanced planning systems. OR Spectr 31(1):1–3

Günther HO, Seiler T (2009) Operative transportation planning in consumer goods supply chains. Flex Serv Manuf J 21(1–2):51–74

Hahn CK, Duplaga EA, Hartley JL (2000) Supply-chain synchronization: lessons from Hyundai motor company. Interfaces 30(4):32–45

Ho JC, Chang YL (2001) An integrated MRP and JIT framework. Comput Ind Eng 41(2):173–185

Hüttmeir A, de Treville S, van Ackere A, Monnier L, Prenninger J (2009) Trading off between heijunka and just-in-sequence. Int J Prod Econ 118(2):501–507

Kannegiesser M, Gunther HO (2011) An integrated optimization model for managing the global value chain of a chemical commodities manufacturer. J Oper Res Soc 62(4):711–721

Lang JC (2009) Production and inventory management with substitutions. Springer, Berlin

Lee HL (2002) Aligning supply chain strategies with product uncertainties. Calif Manage Rev 44(3):105–119

Lloret J, Garcia-Sabater JP, Marin-Garcia JA (2009) Cooperative supply chain re-scheduling: the case of an engine supply chain. In: Springer B (ed) Lecture notes in computer science, vol 5738/2009, pp 376–383

Maheut J, Garcia-Sabater JP, Mula F (2012) A supply chain operations lot-sizing and scheduling model with alternative operations. In: Sethi SP et al (ed) Industrial engineering: innovative networks. Springer London

Meyr H (2004) Supply chain planning in the German automotive industry. OR Spectr 26(4):447–470

Meyr H, Wagner M, Rohde J (2005) Structure of advanced planning systems. In: Staedtler H, Kilger C (eds) Supply chain management and advanced planning: concepts, models, software and case studies, 3rd edn. Springer, Berlin, pp 109–115

Monden Y (1981) Production smoothing. Industrial engineering, pp 42–51

Monden Y (1994) Toyota production system. An integrate approach to just in time. Chapman & Hall, London

Mula J, Peidro D, Diaz-Madroñero M, Vicens E (2010) Mathematical programming models for supply chain production and transport planning. Eur J Oper Res 204(3):366–390

Ozdamar L, Yazgac T (1999) A hierarchical planning approach for a production-distribution system. Int J Prod Res 37(16):3759–3772

Parush A, Hod A, Shtub A (2007) Impact of visualization type and contextual factors on performance with enterprise resource planning systems. Comput Ind Eng 52(1):133–142

Piper CJ, Vachon S (2001) Accounting for productivity losses in aggregate planning. Int J Prod Res 39(17):4001–4012

Puig-Bernabeu X, Maheut J, Garcia-Sabater JP, Lario FC (2010) Algorithm for planning the supply of product with FTL strategy in lean environment: an industrial case. ICOVACS 2010 Valencia—international conference on value chain sustainability, pp 174–182

Quadt D, Kuhn H (2008) Capacitated lot-sizing with extensions: a review. 4OR Q J Oper Res 6(1):61–83

Rashid MA, Hossain L, Patrick J (2002) Enterprise resource planning solutions & management. In: Nah FF-H (ed) Enterprise resource planning solutions & management. IRM Press, USA

Riezebos J, Klingenberg W, Hicks C (2009) Lean production and information technology: connection or contradiction? Comput Ind 60(4):237–247

Sillekens T, Koberstein A, Suhl L (2010) Aggregate production planning in the automotive industry with special consideration of workforce flexibility. Int J Prod Res iFirst:1–24

Simpson NC, Erenguc S (2001) Modeling the order picking function in supply chain systems: formulation, experimentation, and insights. IIE Trans 33(2):119

Stadtler H (2005) Supply chain management and advanced planning—basics, overview and challenges. Eur J Oper Res 163(3):575–588

Stadtler H, Kilger C (2002) Supply chain management and advanced planning: concepts, models, software and case studies. Springer, Berlin

Sugimori Y, Kusunoki K, Cho F, Uchikawa S (1977) Toyota production system and Kanban system materialization of just-in-time and respect-for-human system. Int J Prod Res 15(6):553–564

Wang RC, Liang TF (2004) Application of fuzzy multi-objective linear programming to aggregate production planning. Comput Ind Eng 46(1):17–41

Wang S, Sarker BR (2005) An assembly-type supply chain system controlled by kanbans under a just-in-time delivery policy. Eur J Oper Res 162(1):153–172

Yokoyama M (2008) Flow-shop scheduling with setup and assembly operations. Eur J Oper Res 187(3):1184–1195

Author Biographies

José P. Garcia-Sabater is Professor of Operations Management in the Departamento de Organización de Empresas at the Universidad Politécnica de Valencia. He received his Ingeniero Industrial Degree and his PhD from the University Politécnica de Valencia (Spain). He also received a Combined Eng Degree from Coventry University (UK). Professor Garcia-Sabater's research and teaching interests are in the areas of supply chain management, operations management, and management science. He is member of the Scientific Committee of congresses and Editorial Boards. His work has appeared in journals such as European Journal of Operational Research, International Journal of Production Economics, Fuzzy Sets and Systems, Discrete Applied Mathematics, and others.

Julien Maheut is a researcher at Research Group ROGLE at the Universidad Politécnica de Valencia (Spain). He is currently coursing a PhD program in Operational Research and Supply Chain Management Advanced Models at the Universidad Politécnica de Valencia (Spain) sponsored by a Val I+D grant from the Generalitat Valenciana. Julien Maheut has got a Master in Science in Supply Chain Management & Logistics from UPV and a Diplôme d'ingénieur and a Master's Degree from Arts et Métiers ParisTech. His research interests include industrial engineering, supply chain management, collaborative planning, modeling and simulation, and multiagent system.

Julio J Garcia-Sabater is lecturer in the Departamento de Organización de Empresas at the Universidad Politécnica de Valencia (Spain). He lectures on management and lean manufacturing. He is foundation member of Research Group ROGLE where he develops his activities in different projects. His main research fields are Continuous improvement and lean manufacturing systems. With regard to these areas she has participated in public and private subsidy projects for some companies in Spain.